General Motors

Thermoplastic Engineering Design

In the early 1990s, designing and molding a new production-quality thermoplastic automobile part cost hundreds of thousands of dollars and often required 5 to 10 trial-and-error cycles before a part with the correct dimensions, shape, stiffness, and strength could be manufactured. Engineers at General Motors (GM) and General Electric (GE) Plastics believed that they could apply virtual design methods to improve the thermoplastic parts development process. To transform the trial-and-error development process into a design process that utilized computer simulations, the two companies formed a joint venture. Because existing internal, piecemeal funding was inadequate to stimulate the collaborative, pre-competitive research needed to integrate all the development aspects, GM and GE applied for and were awarded Advanced Technology Program (ATP) cost-shared funding in 1992 for a five-year project called Thermoplastic Engineering Design (TED). The TED project team comprised six subcontractors, including software developers AC Technology (now Moldflow Corporation) and Hibbit, Karlsson & Sorenson, Inc. and several universities.

After the end of the ATP-funded project in 1997, the TED program successfully streamlined the development of new thermoplastic parts and shortened time to market for new parts by reducing the number of development and testing cycles, the number of test molds produced, and the number of rejected prototype parts. The TED process decreased internal testing time and improved reliability, and researchers incorporated their data into commercially available thermoplastics design software. In 1999, GM spun off Delphi Corporation, an auto parts manufacturer that currently uses the TED process to produce thermoplastic parts for many original equipment manufacturers and after-market suppliers. Global thermoplastics industry sales are strong and are expected to continue to grow at six percent annually through 2006. This provides continued opportunities to implement the TED technology. However, GM and GE Plastics have reduced their U.S. thermoplastics research and production due to strong foreign competition.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 92-01-0040 were collected during July - September 2003.

Existing Parts Development Process Was Slow and Costly

Injection molding of thermoplastics involves converting plastics into products by injecting molten plastics, mixed with glass fibers for strength and stiffness, into mold cavities of complex shapes under heat and high pressure. In 1992, the automotive industry relied heavily on injection-molded thermoplastics; each vehicle contained several hundred injection-molded parts. The existing iterative process to develop a new part was time-consuming and expensive. Engineers first developed specifications, then created prototype molds, determined the required processing conditions, tested the resulting parts, and modified the molds. They often needed to repeat this cycle 5 to 10 times before they were able to produce a satisfactory part with acceptable processing conditions. Because many thermoplastic parts change with each new model year, engineers must continually develop and test new mold designs to make the updated parts.

The development of new injection-molded components relied on the integration of two inter-related processes: flow analysis (how the part is manufactured) and structural analysis (how the part performs). Flow analysis includes considering temperature, the flow of the hot liquid plastic in the mold, and the shrinkage and warpage that occurs in the cooling process. Engineers had to determine where to put the gates (or injection ports) in the mold design. Placement of the gates is important, because the fibers align with the flow direction, which affects the strength and stiffness of the resulting part. The thermoplastic is stronger when the fibers are aligned in the same direction. The part's strength is greatest in the direction of the fibers; in other directions, it is weaker. This directional difference in properties is called anisotropy, which was an important area of focus in the ATP-funded project. Ideally, the fibers must align in the direction that strength and stiffness are needed. Structural analysis requires testing strength in performance conditions. The initial mold design must take into account these performance strength requirements.

After a prototype part was produced, the researchers tested its performance to see how much stress and heat the part could tolerate under normal operating conditions or in an accident. If a given part failed to meet performance requirements, engineers had to redesign the mold.

In 1992, the initial development cost of a single auto body panel was as high as $500,000, with 5 to 10 molding trials required to produce an acceptable part. If General Motors (GM) and General Electric (GE) could eliminate one trial cycle, manufacturers would save $40,000 and six weeks of development time.

GM and GE Proposed to Integrate Thermoplastic Molding and Performance Design

GM and GE Plastics proposed to link the mold design and performance design processes through virtual simulations in order to streamline thermoplastic parts development. GM and GE had been independently conducting limited research in virtual design, but were unable to make strides due to limited funding. GE had focused on raw materials, while GM had focused on end products. The companies formed a joint venture and sought ATP support to foster collaboration on end-to-end design. In 1992, they were awarded $5.78 million in cost-shared funding for a five-year project. The joint venture proposed to develop comprehensive virtual design processes for thermoplastics that would enable them to create the most cost-effective design with the best processes and materials. Their proposed research involved using modeling software and compiling data on materials, molding, and the performance of the resulting parts. The research team called the process "Thermoplastic Engineering Design (TED)." They desired a mechanics-based engineering design approach similar to what the metals industry had developed over many years. However, using plastics with additives, such as fibers and fillers, increased the design complexity. Also, plastics fail differently than metals and are more sensitive to time and temperature. Design and testing required an interdisciplinary understanding of microstructure, material properties, design methods, manufacturing processing, assembly, parts performance, and recycling considerations in order to predict outcomes and reduce the trial-and-error cycle.

The development of new injection-molded components relied on the integration of flow analysis and structural analysis.

The joint venture enlisted the support of six subcontractors: AC Technology (maker of C-MOLD mold-development software [now Moldflow Corporation]); Hibbit, Karlsson & Sorenson, Inc. (maker of ABAQUS performance-testing software); Michigan State University; University of Massachusetts-Lowell; and Stanford University. ATP support facilitated collaboration between the project members and allowed research efforts to increase fourfold, to about 50 cross-disciplinary researchers and engineers. The TED project stimulated synergy between university research, materials production, mold design, and parts performance.

Joint Venture Identifies Primary Technical Goals

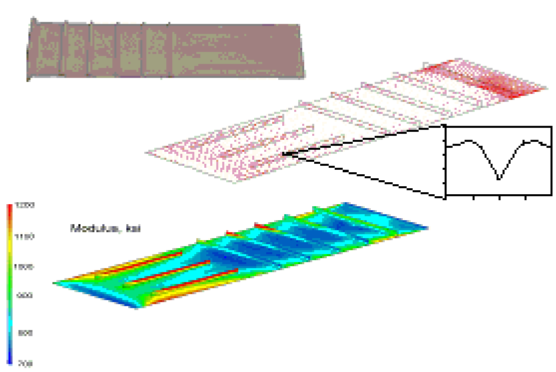
The GM and GE engineers and researchers intended to reduce the expense and development cycle time for thousands of new thermoplastic parts. ATP support allowed the TED project engineers to cooperate on three primary goals:

1. Develop comprehensive mechanics-based design models (e.g., microstructure, materials properties, fiber alignment and related strength and stiffness, parts geometry, and ultimate parts performance)

2. Assess past performance and incorporate the design knowledge into engineering tools (e.g., software simulations, design manuals, and engineering databases)

3. Test the technology in GM and GE manufacturing applications and transfer this technology to a broad manufacturer/supplier base (e.g., Does the part deform and/or break under impact? How does it perform over time? How much temperature change can it tolerate?)

To understand the relationship between processing conditions and materials characteristics, the researchers began by molding plaques (rectangular pieces of plastic) under very controlled processing conditions. The team entered the processing conditions into the C-MOLD and ABAQUS software programs and monitored microstructure, temperature, cooling time, pressure, and other variables. They developed a “TED Calculator” that compared the outcome with the predictions, making refinements as needed. The researchers then studied the results, looking at dimensions and warping, fiber length and orientation/alignment, stiffness and strength, impact resistance, and other parts characteristics. The TED process allowed them to predict these properties, so they could reduce the number of trial-and-error cycles necessary to develop new parts. After they performed a number of trials using different models, their predicted values agreed with the experimental results.



Top: Researchers used representative plaques to test thermoplastic materials for a range of properties. These experimental data are compared to computer predictions and provide the basis for improving predictive models.
Middle: Process simulation predictions of fiber orientation can be represented visually.
Bottom: Predicted fiber orientation, combined with material data, can be used to predict the modulus (stiffness variation) of the test plaque.

Finally, researchers tried to predict failure (e.g., breaks or cracks) based on fiber orientation and other experimental data. Software tools and new ATP developed failure theories helped to predict the variation in strength of a molded component and the in strength of a molded component and the crack initiation locations. Complex-shaped components performed differently than the experimental plaques. The researchers were able to refine the models developed in order to improve the accuracy of their predictions for any shapes.

TED Project Meets Technical Goals

The TED process made significant strides in improving the ability to use computer software to design and predict the dimensional and mechanical performance of injection-molded prototype parts. The project team accomplished its three primary technical goals, and the resulting process reduced the trial-and-error cycles for new parts development. One important outcome was the linking of the two commercial virtual prototype design software programs, C-MOLD (now Moldflow) and ABAQUS, to combine mold design and parts performance. Moldflow and ABAQUS still use the techniques developed in TED; in fact, Hibbit, Karlsson & Sorenson currently markets this Moldflow-ABAQUS interface.

The TED project stimulated synergy between university research, materials production, mold design, and parts performance.

The team compiled data from trials, and they incorporated the data into internal design manuals and databases for prototype development. Engineers used the results from tests made on numerous existing components (e.g., intake manifolds, radiator tanks, transmission covers, wiper arms, fan blades, door components, and body side moldings) to predict the performance of new parts.

TED Knowledge Is Disseminated Widely

The TED project team shared its knowledge extensively through the following:

- Provided training workshops for GM and GE Plastics engineers on how to incorporate TED strategies and tools

- Published highlighted accomplishments and results of the TED project in numerous academic publications

- Founded the National Thermoplastics Engineering Design Association, a direct output of the ATP-funded project, which has approximately 1,500 members from 300 companies and institutions, where members can learn about the TED modeling tools

- Gave public presentations at workshops and conferences and contributed to the development of a graduate-level course offered at Michigan State University

Economic Changes Stimulate Corporate Shift

In the late 1990s, U.S. manufacturers were increasingly outsourcing parts production in order to increase efficiency and reduce costs. Two years after the ATP-funded project had ended, GM spun off Delphi Corporation in 1999, an operation that included the majority of GM's thermoplastics production. Delphi now uses the TED process to produce thermoplastic parts for multiple original equipment manufacturers and after-market suppliers. GM has continued limited thermoplastics research.

Improved Thermoplastic Design Provides Economic Benefits

Reducing development cycle time and cost was the primary benefit of the TED process, but it is difficult to measure cost reduction down to the level of specific parts. However, GM, GE, and Delphi have demonstrated several specific benefits that resulted from their project research:

- Delphi now designs thermoplastic parts that have predictable fatigue life (length of time a part can sustain repeated loading), impact strength, and, in some cases, shrinkage/warpage properties.

- The TED program led to the development of a new International Standards Organization (ISO) Standard, 294-5, to generate the anisotropic mechanical data needed for thermoplastics part design.

- A Moldflow and ABAQUS interface, which was designed based on TED principles, provides engineers commercially available software to integrate virtual mold design with parts performance.

- The project research resulted in one U.S. patent and two project awards.

- Delphi continues to refine TED design principles and applies them to many re-engineered and new parts. For example, engineers were dealing with a thermoplastic radiator tank, which fits on both sides of a metal radiator. The tanks must pass a long term fatigue test. Using the TED process, the fatigue lifetime was accurately predicted by taking into account the temperature, glass fiber orientation, ABAQUS stress analysis, and an ATP developed fatigue cracking theory. In some cases tanks were also cracking during assembly to the metal radiator. Again, using the TED process, the assembly equipment was redesigned to eliminate the cracking. These ATP developed virtual part design methodologies remain in place at Delphi for all new plastic radiator tanks.

- GM is continuing limited TED research internally. At GM’s Powertrain division, engineers now have a virtual part design capability to improve stiffness and strength for their injection-molded engine components. One of the GM test cases was a plastic intake manifold. Injection-molded, glass-fiber-filled plastic intake manifolds have to withstand an overpressurization test, where they are pressurized to simulate a backfire inside the manifold. GM used C-MOLD to determine the principal material directions and ABAQUS to predict the burst pressure of these parts. Engineers used TED methods to modify the design of the product, significantly raising the burst pressure. This modified design was generated in one iteration, rather than the 4-5 that might have been required without the TED modeling.

- GE Plastics provides improved raw materials and technical support to its other thermoplastics customers for use in molding processes for business equipment (e.g., monitors and printer housings), telecommunications (e.g., cellular telephones), and optical media (e.g., CDs and DVDs).

TED Development Continues

As of 2003, GE Plastics, GM, and Delphi researchers were continuing to perform research on the predictive models for virtual design. Based on the TED process, GM and GE Plastics are developing new high-performance thermoplastic parts, using new materials in order to produce parts that support heavier loads. Delphi, as a subcontractor to GM and other manufacturers, produces many thermoplastic parts using the TED process. Even after the ATP-funded project concluded, the company continues internal research and still maintains a joint development agreement with Moldflow software, which originated with the TED project. Moldflow sells this modeling software commercially.

Demand for Thermoplastics Rises as Prices Drop

The overall use of thermoplastics in automobiles has increased dramatically since the TED project began, increasing competition and reducing prices. By 1997, North American automakers were using 56 percent more fiberglass than in 1990 (352 million pounds, compared with 226 million pounds). The use of nylons in engine components in U.S.-built cars grew 24 percent from 1990 to 2002 (97 million pounds in 1990, 100 million pounds in 1995, and 120 million pounds in 2002, mostly glass- or mineral-reinforced). While the entire U.S. market for thermoplastics is projected to grow 6.4 percent annually from 2003 through 2006, the most rapid growth will be in automotive, medical, and industrial applications. The thermoplastics industry is strong and competitive, and TED strategies and tools allow manufacturers to produce these thermoplastic components more efficiently.

Conclusion

The use of thermoplastics in the automotive industry has grown steadily at approximately six percent per year since the early 1990s. Virtual thermoplastics design had the potential to reduce high development and manufacturing costs in automobiles. In 1992, General Motors (GM) and General Electric (GE) Plastics began a collaborative project, with ATP funding support, to explore this design innovation, called Thermoplastic Engineering Design (TED). TED researchers proposed to develop new virtual design methods for thermoplastics parts development. They sought to optimize their understanding of the complex interactions between plastic materials the manufacturing process, and the part geometry (engineering application) in order to reduce time to market and improve automotive parts' performance. The joint venture successfully developed models to virtually design and manufacture prototype thermoplastic parts. These models account for temperature, material content, warping, and structural integrity during performance.

The TED researchers shared their results extensively. They incorporated their data into commercially available software, Moldflow (formerly C-MOLD) and ABAQUS, for virtual mold and performance design; this led to an interface between ABAQUS and Moldflow software, which benefits many thermoplastics designers. Furthermore, TED researchers developed a new international engineering standard, received one patent, published their results widely within the thermoplastics engineering community, formed the National Thermoplastic Engineering Design organization with approximately 1,500 members, and held many workshops.

As a result of increasing foreign competition and a need to remain competitive, in 1999 GM spun off Delphi Corporation, which produces thermoplastic components for GM and other manufacturers. While GM and GE Plastics have reduced their U.S. thermoplastics research and production, the industry continues to grow and remain competitive. Delphi currently uses the TED process to produce thermoplastic parts for many original equipment manufacturers and after-market suppliers.

PROJECT HIGHLIGHTS
General Motors

Project Title: Thermoplastic Engineering Design (Engineering Design with Injection-Molded Plastics)

Project: To develop a scientific understanding of the relationship between processing, part geometry, microstructure, and part performance for fiber-reinforced molded thermoplastic parts and embody this knowledge in an integrated thermoplastic engineering design methodology (virtual design).

Duration: 10/1/1992-9/30/1997
ATP Number: 92-01-0040

Funding (in thousands):

ATP Final Cost	$5,784	48.4%
Participant Final Cost	6,166	51.6%
Total	$11,950	

Accomplishments: With ATP funding, General Motors (GM), Delphi Corporation (formerly part of GM), and General Electric (GE) Plastics have developed models and generated data for "virtual design" in order to improve the design and development of thermoplastic automotive parts. The project team linked two commercial software tools, Moldflow (formerly C-MOLD) and ABAQUS, with new failure theories for plastics in order to integrate mold design with parts performance. The companies continue to enhance these software tools, and failure models which benefits thermoplastics engineers in general.

Researchers implemented the Thermoplastic Engineering Design (TED) process within GM and GE Plastics both to rework existing parts and also to develop new parts. They formed the National Thermoplastics Engineering Design Association (NTEDA) to transfer the TED methods to design engineers at interested U.S. manufacturers. They won the following awards for their achievements:

- Best Paper Award from the Society of Plastics Engineers Product Design and Development Division, May 2001. J. F. O'Gara, P. H. Foss, and J. P. Harris for "Reinforced Plastic Design: Microstructure and Stiffness of Tensile Bars," Annual Technical Conference (ANTEC) '01 Preprints, Society of Plastics Engineers.

- Campbell Award, 2001. P. H. Foss and C. C. Mentzer for "Process Modeling and Performance Predictions of Injection Molded Polymers." This internal GM research and development award recognizes researchers for outstanding contributions to pure or applied science.

GE received the following patent for technology related to the ATP-funded project:

- "Devices and methods for measurements of barrier properties of coating arrays"
(No. 6,383,815: filed April 4, 2001; granted May 7, 2002)

The project also resulted in the development of a new International Standards Organization (ISO) Standard:

- "Injection molding of test specimens of thermoplastic materials-Part 5: Preparation of standard specimens for investigating anisotropy"
(ISO 294-5, out of technical committee 61; Stage date 12/13/2001)

This project led to many publications and workshops, which are listed at the end of this report.

Commercialization Status: The results of the TED project significantly affected commercial software for design simulations, linking Moldflow, a molding-process software, with ABAQUS, a performance-testing software. Hibbit, Karlsson & Sorenson sells the interface, called "ABAQUS Interface for Moldflow." These virtual design tools have shortened development time and have improved the performance of thermoplastic parts, which has benefited many manufacturers. The project's focus was on improving the development process, so the project has impacted many parts (e.g., Delphi's thermoplastic radiator tank and many other parts; GM's injection-molded plastic intake manifold and other engine components; GE Plastics' improved raw material, which is used in business equipment, optical media, and telecommunications devices).

Outlook: The outlook for TED technology is good. The technology is available to plastics engineers through the commercial off-the-shelf software, Moldflow and ABAQUS. GM, GE Plastics, and Delphi Corporation continue to develop and use the technology internally. Benefits of the ATP-funded technology continue to accrue for consumers: sales of thermoplastics are high, prices are low, and parts last longer. Thermoplastics sales are expected to grow at 6.4 percent per year through 2006, with strong foreign competition.

Composite Performance Score: * * *

PROJECT HIGHLIGHTS
General Motors

Company:

General Motors
Composites Processing Group
Materials and Processes Lab
GM R&D and Planning, MC: 480-106-224
30500 Mound Road
Warren, MI 48090-9055

Contact: Howard W. Cox
Phone: (586) 986-1203

Subcontractor:

Moldflow Corporation (formerly AC Technology)
2353 N. Triphammer Road
Ithaca, NY 14850

Hibbit, Karlsson & Sorenson, Inc.
1080 Main Street
Pawtucket, RI 02860

Michigan State University
Department of Chemical Engineering
2527 Engineering Building
East Lansing, MI 48824-1226

Stanford University
Mechanical Engineering Department
Terman Engineering Center 509
Stanford, CA 94305-4021

University of Massachusetts-Lowell
Plastics Engineering Department
One Lowell Avenue
Lowell, MA 01854

Publications and Presentations:

The joint venture members held numerous workshops to share project knowledge with design engineers at GM, GE, and engineering firms, including the following:

- Trantina, G. G., and M. G. Wyzgoski. “Engineering Design with Injection Molded Thermoplastics,” Society of Plastics Engineers (SPE) ANTEC ’94 Preprints, May 1994.
- Foss, P. H., H. H., Chiang, L.P. Inzinna, C. L. Tucker, and K. F. Heitzmann. "Experimental Verification of C-MOLD Fiber Orientation Predictions," presentation at the C-MOLD Users' Group meeting, Dearborn, MI, September 1994.
- Foss, P. H., R. M. Shay, and C. M. Mentzer. "Experimental Verification of C-MOLD Shrinkage Predictions," presentation at the C-MOLD Users' Group meeting, Dearborn, MI, September 1994.
- Trantina, G. G., and M. G. Wyzgoski. "Engineering Design with Injection Molded Thermoplastics for Automotive Application," 1994 International Body Engineering Conference, Detroit, MI, September 1994.
- Held the first TED workshop on "Mechanical and Dimensional Performance of Injection-Molded Thermoplastic Parts" on February 23, 1995 in Troy, MI with more than 70 GM engineers. Held two additional GM workshops for Delphi in Rochester, NY and Anderson, IN.
- Held first NTEDA workshop on March 7, 1995 for 50 engineers representing a variety of plastics industries. Held 12 workshops in 1995 that addressed approximately 550 engineers and designers.
- Foss, P. H., J. P. Harris, J. F. O'Gara, L. P. Inzinna, E. W. Liang, C. M. Dunbar, C. L. Tucker III, and K. F. Heitzmann. "Experimental Verification of C-MOLD Modulus and Fiber Orientation Predictions," presentation at the C-MOLD Users' Group meeting, Dearborn, MI, September 1995.
- Shay, Jr., R. M., P. H. Foss, and C. C. Mentzer. "Comparison of C-MOLD Predictions and Experimental Shrinkages," presentation at the C-MOLD Users' Group meeting, Dearborn, MI, September 1995.
- Liang, E. W., V. K. Stokes, L. P. Inzinna, J. F. O'Gara, and J. P. Harris. "Tensile Modulus of Injection-Molded Short-Fiber Reinforced Thermoplastics-Experiment and Prediction," 1995 RETEC, Atlanta, GA, September 13, 1995.
- Held GM workshops on October 31, 1995 and November 2, 1995.
- Hasan, O. A. "The Mechanical Behavior of Rubber-Modified Thermoplastics," invited lecturer at Drexel University, November 1995 and ASME Winter Meeting, November 1995.
- Submitted research on fiber length and orientation measurements to the Measurement Science Conference in Anaheim, CA, January 1996.
- Held NTEDA workshop at the Design Engineering Show in Chicago, IL on March 20, 1996. By that time, NTEDA had 1,500 members from 300 different companies and institutions.

PROJECT HIGHLIGHTS
General Motors

- Michigan State University developed a graduate-level course, "The Design for Manufacture of Injection-Molded Parts," based on the TED project, 1996.

- Held technical sessions, "Fatigue of Glass Fiber Reinforced Injection Molded Plastics I. Stress-Lifetime Data" and "II. Tensile Versus Flexural Loading," SPE ANTEC Meeting, May 2001.

- Held a technical session for product design and development, "Product Design and Development Methods to Optimize Plastics Part Designs: Development of an ISO Standard for Determining Anisotropic Properties of Glass-Filled Thermoplastics," May 5, 2003 conference for ANTEC.

The team made the technology widely available through many publications:

- Bushko, W. C., and V. K. Stokes. "The Effects of Differential Mold-Surface Temperatures on the Warpage of Packed Injection-Molded Parts," Proceedings of the Society of Plastics Engineers 52nd Annual Technical Conference, San Francisco, CA, May 2-6, 1994, pp. 506-512.

- Bushko, W. C., and V. K. Stokes. "Shrinkage of Packed Injection-Molded Parts: Simulation of Gate Freeze-Off Effects," Proceedings of the Society of Plastics Engineers 52nd Annual Technical Conference, San Francisco, CA, May 2-6, 1994, pp. 559-564.

- Stokes, V. K. "The Hot-Tool Welding of Acrylonitrile-Butadiene-Styrene," Proceedings of the Society of Plastics Engineers 52nd Annual Technical Conference, San Francisco, CA, May 2-6, 1994, pp. 1327-1332. o Trantina, G. G., and M. G. Wyzgoski. "Engineering Design with Injection Molded Thermoplastics," Society of Plastics Engineers (SPE) ANTEC '94 Preprints, May 1994.

- Bushko, W. C., and V. K. Stokes. "The Effects of Differential Mold Temperatures on the Warpage of Injection-Molded Parts," presented at the ASME International Congress and Exposition, Chicago, IL, November 6-11, 1994. Paper included in Advances in Computer-Aided Engineering (CAE) of Polymer Processing, edited by K. Himasekhar, V. Prasad, T. A. Osswald, and G. Batch, MD-Vol. 49/HTD-Vol. 283, pp. 137-161, American Society of Mechanical Engineers, NY, 1994.

- Bushko, W. C., and V. K. Stokes. "Solidification of Thermoviscoelastic Melts. Part I: "Formulation of Model Problem," Polymer Engineering and Science, Vol. 35, No. 4, pp. 351-364, February 1995. Part II: "Effects of Processing Conditions on Shrinkage and Residual Stresses," pp. 365-383.

- Foss, P. H., H. H. Chiang, L. P. Inzinna, C. L. Tucker III, and K. F. Heitzmann. "Experimental Verification of C-MOLD Modulus and Fiber Orientation Predictions," Society of Plastics Engineers (SPE) ANTEC '95, Preprints, May 1995.

- Woods, J. T., R. P. Nimmer, and K. F. Ryan. "The Development and Validation of Rate Dependent Brittle Failure Criterion for Polycarbonate and Polyetherimide," ANTEC 1995, Boston, MA.

- Bushko, W. C., and V. K. Stokes. " The Effects of Boundary Conditions on the Dimensional Changes and Residual Stresses in Injection-Molded Polycarbonate Parts," Proceedings of the Society of Plastics Engineers 53rd Annual Technical Conference, Boston, MA, May 7-11, 1995, pp. 484-490.

- Stokes, V. K. "Experiments on the Hot-Tool Welding of Polycarbonate," Proceedings of the Society of Plastics Engineers 53rd Annual Technical Conference, Boston, MA, May 7-11, 1995, pp. 1229-1233.

- Stokes, V. K. "Toward a Weld-Strength Data Base for Vibration Welding of Thermoplastics," Proceedings of the Society of Plastics Engineers 53rd Annual Technical Conference, Boston, MA, May 7-11. 1995, pp. 1280-1284.

- Bushko, W. C., and V. K. Stokes. "The Effects of Boundary Conditions on the Shrinkage and Residual Stresses in Injection-Molded Parts," presented at the ASME Joint Applied Mechanics and Materials Summer Meeting, Los Angeles, CA, June 28-30, 1995. Paper included in Current Research in the Thermo-Mechanics of Polymers in the Rubbery-Glassy Range, edited by M. Negahban, AMD-Vol. 203, pp. 129-158, American Society of Mechanical Engineers, NY, 1995.

- Shay, Jr., R. M., P. H. Foss, and C. C. Mentzer. "Comparison of C-MOLD Predictions and Experimental Shrinkages," 1995 Automotive RETEC Preprints, SPE, November 1995.

- P. H. Foss. "Experimental Verification of Finite Element Predictions of Shrinkage, Fiber Orientation and Modulus," Autofact 1995 Preprints, SME, November 1995.

PROJECT HIGHLIGHTS
General Motors

- Bushko, W. C., and V. K. Stokes. "Solidification of Thermoviscoelastic Melts. Part III: Effects of Mold Surface Temperature Differences on Warpage and Residual Stress," Polymer Engineering and Science 36 (3): 322-335, February 1996.

- Bushko, W. C., and V. K. Stokes. "Solidification of Thermoviscoelastic Melts. Part IV: Effects of Boundary Conditions on Shrinkage and Residual Stresses," Polymer Engineering and Science 36 (5): 658-675, March 1996.

- Hasan, O. A. "Use of Deformation Maps in Predicting Time-Dependent Response of Thermoplastics," ANTEC, 1996.

- Foss, P. H., J. P. Harris, J. F. O'Gara, L. P. Inzinna, E. W. Liang, C. M. Dunbar, C. L. Tucker III, and K. F. Heitzmann. "Prediction of Fiber Orientation and Mechanical Properties Using C-MOLD and ABAQUS," ANTEC '96 Preprints, SPE, May 1996.

- Shay, Jr., R. M., P. H. Foss, and C. C. Mentzer. "Comparison of C-MOLD Predictions and Experimental Shrinkages: Fiber-Filled Materials," ANTEC '96 Preprints, SPE, May 1996.

- Wyzgoski, M. G., and G. E. Novak. "Fatigue Fracture of Reinforced Plastics: Measurements and Predictions," ANTEC '96 Preprints, SPE, May 1996.

- V. K. Stokes. "Cross-Thickness Vibration Welding of Polycarbonate, Polyetherimide, Poly(Butylene Terephthalate), and Modified Polyphenylene Oxide," Polymer Engineering and Science 37 (4): 715-725, April 1997.

- VerWeyst, B. E., C. L. Tucker, and P. H. Foss. "The Optimized Quasi-Planar Approximation for Predicting Fiber Orientation in Injection-Molded Composites," International Polymer Processing, 12:238-248, 1997.

- VerWeyst, B. E. Ph.D. Dissertation, "Numerical Predictions of Flow-Induced Fiber Orientation in Three-Dimensional Geometries," University of Illinois at Urbana-Champaign, 1998.

- VerWeyst, B. E., C. L. Tucker, P. H. Foss, and J. F. O'Gara. "Fiber Orientation in 3-D injection Molded Features: Prediction and Experiment," International Polymer Processing, 14:409-420, 1999.

- VerWeyst, B. E. and C. L. Tucker, III. "Fiber Suspensions in Complex Geometries: Flow/Orientation Coupling," Can. J. Chem. Eng., 80:1093-1106, 2002.

- Wyzgoski, M. G., J. A. Krohn, and G. E. Novak. "Fatigue of Glass Fiber Reinforced Injection Molded Plastics I. Stress-Lifetime Data," Polymer Composites urnal, accepted for publication, 2004.

- Wyzgoski, M. G., J. A. Krohn, and G. E. Novak. "Fatigue of Glass Fiber Reinforced Injection Molded Plastics II. Tensile Versus Flexural Loading," Polymer Composites Journal, accepted for publication, 2004.

Research and data for Status Report 92-01-0040 were collected during July - September 2003.